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FREEZING INJURY TO POTATOES WHEN UNDERCOOLED.[1]

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SCOPE OF THE INVESTIGATIONS.

Each year the loss to growers, shippers, and carriers of potatoes due to freezing reaches an enormous figure. This is particularly true of the late or main crop produced in the Northern States. This crop is usually in constant danger of exposure to freezing temperature from just before it is harvested until it reaches the consumer. There are two general classes of frost-injured potatoes—those frozen solid and subject to collapse immediately on thawing and those that show evidence of injury only on being cut open a few hours after being warmed. The first class of injured potatoes is easily identified by the soft, wet condition that develops on thawing. This type of injury is due to the potato being subjected to freezing at very low temperatures or to prolonged exposure at higher freezing temperatures. The second type of injury is not apparent on superficial examination. It is due to exposure to temperatures just below the freezing point or to a very low temperature for a short time. If after the potato has been thawed a few hours it is cut open, evidences of this type of freezing injury are apparent by the presence of vascular discoloration of three types or a combination of any of the three.

[1] This bulletin gives the results of a portion of the work carried on under the project "Factors affecting the storage life of vegetables."

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PHYSIOLOGY OF THE FREEZING PROCESS.

The frost necrosis of potato tubers is described by Jones, Miller, and Bailey (4)[2] as being characterized by three types, viz, ring, net, and blotch. In the ring type only the vascular ring, an area near the surface, is discolored. In the net type threadlike areas radiating from the center are discolored. The third type is marked by irregular blotched areas. Ordinarily no further change takes place after the injured potato thaws, although in the most severe cases the tubers soon begin to break down if kept warm.

Frost injury seems to be the result of actual ice formation within the potato tissue. Abbe (1), in his investigations of the effect of freezing upon plant tissue, considers that as the tissue cools water exudes from the cells into the intercellular spaces. After sufficient undercooling this water freezes. The concentrated sap remaining in the cells will not freeze until cooled below the freezing point of water. On thawing, this intercellular water escapes by transpiration and the plant wilts. Göppert (3) and Sachs (6) both observed the presence of ice within the cells and the intercellular spaces of plant tissue. However, Sachs found crystals of ice usually present in the intercellular spaces. Müller-Thurgau (5) was one of the first to publish (1880) upon frost injury of potatoes in his investigations upon the freezing point of plant tissue. The phenomena of undercooling were investigated by him to a considerable extent. He showed that plant tissue required undercooling below the true freezing point before actual freezing commences. He also showed that the expressed sap of the potato tuber freezes at a higher temperature than the living tissue. The ultimate freezing point of potatoes is placed at 30.21° F. by Müller-Thurgau and between 28° and 26° F. by Appleman (2). Vaughan and Miller (7) state that "actual freezing does not begin in potatoes until the temperature drops below 28° F." Jones, Miller, and Bailey (4) place the freezing point at 28.4° F.

The author of an unsigned article in the Potato Magazine (8) states that exposure at 30° F. for 9 or 10 hours or at 16° F. for 1 hour will develop signs of frost necrosis. In results published by Wright and Harvey (9) the freezing point varied from 29.67° to 28.13° F. according to variety and season. In this investigation the freezing points of 18 different varieties were determined. The freezing points varied in different varieties and according to family groups. The early and medium-early potatoes froze at a higher point than the purely late varieties. The subject of undercooling was discussed. It was stated that potatoes, since their sap consists of salts, sugar, and other soluble material, freeze at a lower temperature than pure water.

[2] The serial numbers in parentheses refer to "Literature cited" at the end of this bulletin.

It was shown that potatoes could be undercooled several degrees below the true freezing point without actual freezing taking place. In addition, it was shown that when once cooled below the true freezing point the process of undercooling can be terminated at any point by inoculating the tuber. The term "inoculation"[3] is used in this connection to indicate any disturbance which will start crystallization or ice formation. Following inoculation the temperature of the potato rises quickly to the true freezing point, accompanied by the formation of ice within the tissue. Inoculation is caused by some mechanical disturbance, such as a jolt or jar sufficient to cause freezing to commence. It is a well-known fact that water, for example, can be undercooled below its freezing point. After a certain amount of undercooling actual freezing will result from any slight disturbance or by the addition of a crystal of ice.

In the potato, inoculation is readily accomplished by striking or jarring the undercooled tuber. The degree of force necessary to accomplish this is determined by the extent of undercooling. It seems that a potato can be undercooled to such a point that the slightest perceptible jar will instantly inoculate it. Water on the surface or sap from a bruise will prevent a potato from reaching the degree of undercooling it would attain if dry, since this free moisture will freeze at a higher temperature than the living tissue and will in this way inoculate the entire potato. Müller-Thurgau (5) and Jones, Miller, and Bailey (4) found that a freshly cut potato will freeze more quickly; that is, it will not undercool as far as a dry potato.

Müller-Thurgau was of the opinion that the undercooling point varies with the air temperature to which potatoes are exposed. He attempted to justify this view by data. In one instance freezing occurred in two hours at an exposure of 23.9° F. and in another in five hours at an exposure varying from 15.8° to 10.7° F. Jones and his colleagues (4), commenting on these results, state that possibly the earlier freezing at the higher undercooling temperature was due to a more rapid fall in temperature in this case. Data submitted by them and also in Department Bulletin 895, heretofore cited (9), indicate that the degree of undercooling is dependent for one thing upon the rate of fall of temperature. It is also entirely possible that a sudden unnoticed jar might have caused earlier freezing where the undercooling temperature was higher. In Department Bulletin 895 (9, p. 6) a diagram is presented in which results are illustrated when two potatoes were exposed to different temperatures. One potato ex-

[3] It is considered that the term "inoculation" is rightly used here, as it is directly comparable to the process in physical chemistry, known by the same term, in which crystallization is started in a concentrated solution by adding a crystal of the solute or when freezing is started by adding a crystal of ice to pure water that has been undercooled.

posed to a temperature of 8.7° froze in 6 minutes when the actual internal temperature had reached 23° F. The other potato was exposed to 15.8° and froze in 12.5 minutes when the internal temperature had reached 20.2° F. The actual freezing point of both potatoes was 29.15° F. This substantiates the results obtained by Jones, Miller, and Bailey (4). They cite an instance of a tuber freezing in 80 minutes when undercooled to 24.44°, while another exposed to a slowly diminishing temperature did not freeze until 13.1° F. was reached. Another specimen froze in 40 minutes when undercooled to 26.4° while exposed to a rapidly diminishing temperature which had reached 12.2° F. They state that, in general, potatoes do not freeze until exposed to 26.6° F. or lower. To judge from the results submitted in this report it is possibly safe to state that except in the case of accidental inoculation the degree of undercooling at which freezing occurs depends upon the variety, the rapidity with which undercooling progresses, and the length of exposure to a given degree of undercooling.

PLAN OF THE WORK.

In order to apply to the handling of potatoes the knowledge of the process of undercooling and freezing already gained, a series of experiments was conducted at the Arlington cold-storage plant of the Bureau of Plant Industry. It has been noted by potato growers and shippers that sometimes one lot of potatoes while being handled or otherwise disturbed in transit will freeze when another left undisturbed at the same temperature remained uninjured. Some apple handlers are very careful not to jar or jolt frosted apples, because they say it will cause them to bruise and rot. It is a practice among some onion growers to store their onions through very severe winter weather in mows or buildings between layers of hay where they are undisturbed during the winter. These persons will often guard against loose doors or shutters which can be slammed by the wind, as this is liable to cause the onions to freeze and subsequently to rot. Numerous instances are reported where potatoes have been exposed for hours or even days to temperatures below their freezing point without injury. Müller-Thurgau reported having stored potatoes at 32° to 26.6° F. for two weeks without injury. Of course, internal frost injury may have been present without its being detected unless the potatoes were cut open and examined.

In the present work seven standard varieties of potatoes, all true to name and grown under the same conditions by the Bureau of Plant Industry at the Aroostook Farm of the Maine Agricultural Experiment Station, were used. These varieties were the Triumph, Irish Cobbler, Spaulding No. 4, American Giant, Rural New Yorker,

Russet Rural, and Green Mountain. They were all held at 40° F. previous to experimental use.

Storage tests on the seven varieties held at temperatures below the true freezing points were conducted in order to correlate, if possible, the freezing points (Table I) of these varieties as determined by the thermoelectric method described by Wright and Harvey (9) and the actual freezing of the different varieties in storage. These tests were conducted at 28° and 25° F. The higher temperature was chosen because it represented about the minimum degree of undercooling to which the potatoes could be subjected, since it was just below the freezing points of most of the varieties used. The lower temperature was chosen because it was far enough below the freezing points of all varieties to represent a definite degree of undercooling at which freezing quickly follows a very light inoculation. When the potatoes were selected for the freezing tests they were placed in small wooden baskets holding from 8 to 10 specimens, in order that they might cool down without much delay. At the conclusion of each test the potatoes were removed, to be held at ordinary room temperature for about 24 hours before being cut longitudinally for examination. If cut immediately after being removed from storage, no evidence of freezing injury will be apparent unless they have been frozen solid. Unless specially noted, all injury reported is of the vascular type, as described by Jones, Miller, and Bailey.

TABLE I.—*Freezing points of seven varieties of potatoes.*

Variety.	Freezing point.	Variety.	Freezing point.
	°F.		°F.
Triumph	29.04	Rural New Yorker	28.70
Irish Cobbler	29.66	Russet Rural	28.32
Spaulding No. 4	29.33	Green Mountain	28.50
American Giant	29.64		

Tables II and III show the results obtained from these tests at 28° and 25° F. The data presented in Table II show that potatoes did not freeze to any serious extent when exposed to 28° F. for many hours. In experiment No. 1 two specimens of each variety were held seven hours, one specimen of Rural New Yorker being injured. In experiment No. 2 twenty specimens of each variety were held 24 hours. Only two varieties showed injury. These included two specimens of Irish Cobbler and one specimen of the American Giant. In the third experiment two specimens of each variety were held 48 hours, one Rural New Yorker being injured. In experiment No. 4 half-bushel lots of Triumph, Spaulding No. 4, American Giant, and Russet Rural varieties were held in bags for 48 hours with no injury. In experiment No. 5 eleven specimens of each variety were held for 70 hours.

Serious injury was apparent in this experiment. Injury occurred to five specimens of Triumph, six of Irish Cobbler, five of Spaulding No. 4, four of American Giant, one of Rural New Yorker, two of Russet Rural, and one of Green Mountain. The most serious injury occurred in the early-maturing varieties. In experiment No. 6 six tubers of each variety were held 96 hours, with injury occurring to two specimens of Triumph, two of Irish Cobbler, two of American Giant, and one of Russet Rural. The Spaulding No. 4, Rural New Yorker, and Green Mountain varieties suffered no injury. The aggregate injury in this experiment was 17 per cent, while in experiment No. 5 the injury totaled 31 per cent.

TABLE II.—*Freezing injury to seven varieties of potatoes held at 28° F. for different lengths of time.*

Variety.	Number of experiment and duration of exposure.											
	No. 1, 7 hours.		No. 2, 24 hours.		No. 3, 48 hours.		No. 4, 48 hours.		No. 5, 70 hours.		No. 6, 96 hours.	
	Number of specimens.	Number injured.	Number of specimens.	Number injured.	Number of specimens.	Number injured.	Quantity of specimens.	Number injured.	Number of specimens.	Number injured.	Number of specimens.	Number injured.
							Bush.					
Triumph	2	0	20	0	2	0	½	0	11	5	6	2
Irish Cobbler	2	0	20	2	2	0	.....	.....	11	6	6	2
Spaulding No. 4	2	0	20	0	2	0	½	0	11	5	6	0
American Giant	2	0	20	1	2	0	½	0	11	4	6	2
Rural New Yorker	2	1	20	0	2	1	.....	0	11	1	6	0
Russet Rural	2	0	20	0	2	0	½	0	11	2	6	1
Green Mountain	2	0	20	0	2	0	.....	.....	11	1	6	0
Total	14	1	140	3	14	1	2	0	77	24	42	7

In no case at 28° F. were the potatoes frozen solid. A superficial examination would not have revealed any evidence of freezing injury in any of these varieties. It is true that during subsequent storage, however, these internally injured specimens are the first to break down, although these potatoes do not show injury so far as their external appearance is concerned and would be as salable in the ordinary market as the uninjured ones. After a few days at ordinary room temperature they are quite unfit for food. While no serious injury occurred till the potatoes were held at least 70 hours, isolated cases of freezing injury did occur even when potatoes were held only 7 hours. It is difficult to explain these isolated cases. For some unknown reason certain individuals seem to bear much less undercooling than others of the same variety. Similarly, certain varieties bear less undercooling than other varieties. There is a certain varietal difference shown here. The Irish Cobblers seem to be the first to succumb to freezing injury, followed by the Triumph, American Giant, Spaulding No. 4, and Russet Rural varieties. The Rural New Yorker and Green Mountain varieties are the most resistant.

TABLE III.—*Freezing injury to seven varieties of potatoes held at 25° F. for different lengths of time.*

Variety.	Number of experiment and duration of exposure.							
	No. 1, 5 hours.		No. 2, 19 hours.		No. 3, 24 hours.		No. 4, 43 hours.	
	Number of specimens.	Number injured.	Number of specimens.	Number injured.	Number of specimens.	Number injured.	Number of specimens.	Number injured.
Triumph	2	0	6	0	11	5	3	[a] 1
Irish Cobbler	2	0	6	2	11	6	3	[a] 2
Spaulding No. 4	2	0	6	0	11	8	3	1
American Giant	2	0	6	2	11	6	3	3
Rural New Yorker	2	0	6	1	11	5	3	0
Russet Rural	2	0	6	1	11	2	3	[b] 3
Green Mountain	2	0	6	1	11	4	3	1
Total	14	0	42	7	77	36	21	11

[a] Frozen solid.

[b] Two were frozen solid.

In Table III are shown the results obtained when the different varieties were held at 25° F. In experiment No. 1 two specimens of each variety were held 5 hours with no evidence of injury. In experiment No. 2 six specimens of each variety were stored 19 hours, with injury to two Irish Cobblers, two American Giants, one Rural New Yorker, one Russet Rural, and one Green Mountain. It is worthy of note that the Triumph and Spaulding No. 4 varieties, which according to Table I have a comparatively high freezing point, did not show injury in this experiment. In experiment No. 3 eleven specimens of each were held 24 hours, with serious consequences to most of the varieties. Injury was found in five Triumphs, six Irish Cobblers, eight Spaulding No. 4, six American Giants, five Rural New Yorkers, two Russet Rurals, and four Green Mountains. The total injury was 47 per cent. In experiment No. 4 three tubers of each variety were held 43 hours, with injury to one Triumph, two Irish Cobblers, one Spaulding No. 4, three American Giants, three Russet Rurals, and one Green Mountain. Tubers of the Rural New Yorker were not injured; one specimen of Triumph, one of Irish Cobbler, and two of the Russet Rural varieties were frozen solid. The total injury in this experiment was 52 per cent.

Generally speaking, when potatoes of the seven varieties were held for varying lengths of time at 28° or 25° F. they did not freeze in any definite order or with relation to their freezing points. At 28° F. the early-maturing varieties with the higher freezing points possibly showed more freezing injury.

INOCULATION OF UNDERCOOLED POTATOES.

Attention is called to the fact that in the experiments just described the potatoes were purposely held entirely undisturbed, as it had been found that potatoes when undercooled are liable to freeze

when jarred. It is considered highly important to call the attention of growers and shippers to this point, since under some circumstances it would be entirely possible that a lot of potatoes or even other products might be undercooled considerably below the freezing point and escape injury if they remained undisturbed till their temperature was above the freezing point. If it should be found necessary to move such a lot in order to protect them from further lowering of the temperature, this should be very carefully done, having in mind the danger of freezing as the result of jarring or jolting. These statements seem justified and are supported by the results brought out by the following experiments, which were conducted to determine the amount and character of the disturbance necessary to cause freezing when different varieties of potatoes are held at temperatures between 28° and 25° F. The same seven standard varieties before named were used in these experiments.

EXPERIMENT NO. 1.

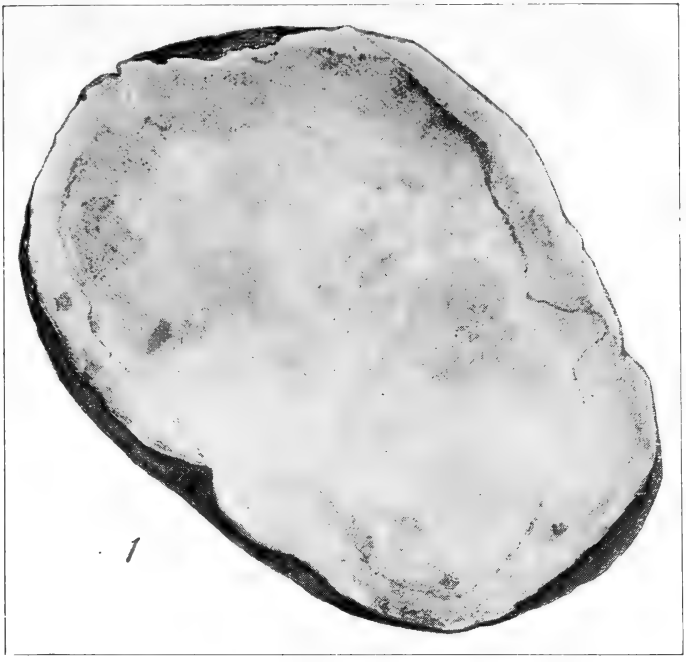
Duplicate lots of potatoes, consisting of a single specimen of each variety, were held between 26° and 27° F. for 5½ hours. Then each specimen in one lot was dropped from a distance of 4 feet to the concrete floor. After 17 hours from the time they were dropped, both lots were removed and held at ordinary room temperature several hours before they were cut open. In the check lot only the Irish Cobbler and the American Giant were injured. All specimens in the treated lot were not only badly bruised, as might be expected from the rough treatment, but they were all frost injured, as was shown by extensive blackened vascular areas of the blotch type. (Pl. I.) None of the potatoes were frozen hard enough to cause collapse of the tissues.

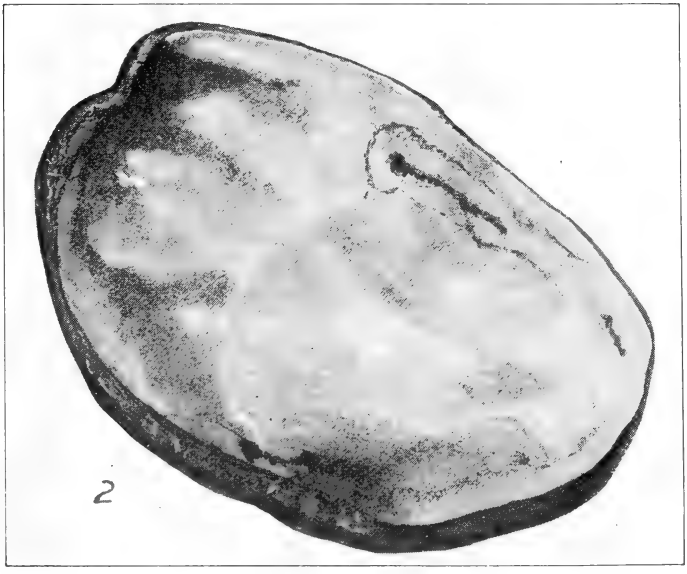
EXPERIMENT NO. 2.

Duplicate lots of one potato of each variety were held at 28° F. for 22 hours. One lot was then dropped as before and left for three hours. Both lots were then removed. As before, at the lower temperature all the dropped potatoes were bruised and showed extreme freezing injury. In the undisturbed check lot only the Irish Cobbler was injured.

EXPERIMENT NO. 3.

Duplicate lots of one potato of each variety were placed at 28° F. for 24 hours. Each specimen from one lot was dropped from a distance of 2 feet, and after another 24 hours all were removed. On the usual examination it was found that these potatoes were badly bruised and showed extensive injury, as before, except the American Giant and Spaulding No. 4 varieties, which showed no frost injury and were not bruised.





FREEZING INJURY TO POTATOES ARTIFICIALLY PRODUCED.

The potatoes were undercooled at 25° F. for 24 hours, then inoculated by dropping 6 inches. In one hour after inoculation they were removed to a warm room. One specimen (Irish Cobbler, fig. 1) shows only slight freezing injury of the ring type. The other specimen (American Giant, fig. 2) shows severe injury of the ring and blotch type.

EXPERIMENT NO. 4.

Duplicate lots of two potatoes of each variety were held at 28° F. for 24 hours, after which all of one lot were dropped 1 foot. After another 24 hours all were removed. Examination showed no bruising; however, most of the potatoes were frozen. The results are shown in Table IV.

TABLE IV.—*Freezing injury to potatoes of seven different varieties undercooled at 28° F. and dropped 1 foot.*

Variety.	Dropped.		Check.	
	Injured.	Uninjured.	Injured.	Uninjured.
Triumph	2	0	0	2
Irish Cobbler	2	0	0	2
Spaulding No. 4	0	2	0	2
American Giant	2	0	0	2
Rural New Yorker	2	0	1	1
Russet Rural	2	0	0	2
Green Mountain	0	2	0	2
Total	10	4	1	13

EXPERIMENT NO. 5.

A total of 24 potatoes of the Rural New Yorker variety were placed at 28° F. After 24 hours 12 were dropped 12 inches. In no case was a potato bruised or even the skin broken. In 4 hours both lots were removed. Examination showed all of the lot that was dropped to be injured by freezing. None of the check lot was injured.

EXPERIMENT NO. 6.

This experiment was conducted to ascertain, if possible, the minimum distance from which an undercooled potato may fall and still succumb to freezing injury. Five lots of 12 potatoes of the Rural New Yorker variety were held at 28° F. for 18 hours. Then lots were dropped 2, 4, and 6 inches, and in one lot each individual was struck with a pencil. After seven hours all were removed. Examination showed that only the potatoes that were struck with the pencil were injured.

EXPERIMENT NO. 7.

Lots of three potatoes of each variety were dropped, as in experiment No. 6, with the exception that each potato was dropped six times instead of once. The results are shown in Table V. Practically the same amount of freezing injury was produced in all dropped potatoes without relation to the length of the fall. The injury produced was of the blotch type. It may be stated here that the potatoes used in this experiment were purposely selected and weighed, so as to have both large and small specimens in each lot, thus varying the force of

the blow caused by the fall. There was apparently no relation between the weight of the potato and the freezing injury. In addition to the lots already described in this experiment, an additional lot of two of each variety was treated by striking each potato sharply with a pencil once, with the results shown in Table V. It is difficult to state why it was necessary to drop the potatoes several times from 2, 4, and 6 inch heights to produce frost injury, while one sharp blow with an ordinary pencil results in serious injury. The possible explanation is that the blow from the pencil caused a more violent concussion in a smaller area, from which the whole potato was inoculated.

TABLE V.—*Freezing injury to potatoes of seven different varieties undercooled at 28° F. and inoculated in different ways.*

Variety.	Dropped 2 inches.		Dropped 4 inches.		Dropped 6 inches.		Struck with pencil.		Check.	
	Injured.	Uninjured.	Injured.	Uninjured.	Injured.	Uninjured.	Injured.	Uninjured.	Injured.	Uninjured.
Triumph	3	0	3	0	3	0	1	1	0	3
Irish Cobbler	3	0	3	0	3	0	1	1	0	3
Spaulding No. 4	1	2	3	0	2	1	1	1	0	3
American Giant	3	0	3	0	3	0	2	0	1	2
Rural New Yorker	3	0	3	0	3	0	2	0	0	3
Russet Rural	3	0	3	0	2	1	2	0	0	3
Green Mountain	3	0	2	1	2	1	2	0	1	2
Total	19	2	20	1	18	3	11	3	2	19

EXPERIMENT NO. 8.

Two lots of one specimen of each variety of potato were held at 28° F. for 24 hours, after which each potato of one lot was repeatedly bounced on the floor for about 10 seconds by dropping it from a height of not over 1 inch. After another 24-hour period all were removed. While none of the bounced specimens showed bruising or mechanical injury, they were all frost injured. The specimens of American Giant and Green Mountain froze solid, with resultant complete collapse on thawing. Of the check lot the Spaulding No. 4 and the Green Mountain varieties showed slight freezing injury.

EXPERIMENT NO. 9.

Lots of three potatoes of each variety were held at 25° F. for 18 hours, after which they were dropped once from distances of 6, 4, and 2 inches. After another hour all were removed. Examination showed that all dropped potatoes were injured, while in the check lot frost injury resulted to only one each of the Irish Cobbler, American Giant, Russet Rural, and Green Mountain varieties.

Several experiments were conducted to test the rate at which the temperature of a potato will fall when exposed to a temperature below its freezing point. Figure 1 illustrates a typical set of results.

A Triumph potato was suspended in a metal container 18 inches long by 4 inches in diameter, which was in turn immersed in a brine tank. Thermoelectric couples were located at the center and near the surface of the potato; also one was suspended in the air 1 inch from the potato. Periodical readings were made from the time the temperature of the potato was near 40° F. The temperature of the atmosphere surrounding the potato gradually fell from 27.2° to 25.6° F. The temperature of the potato at the beginning was 40.8° at the surface

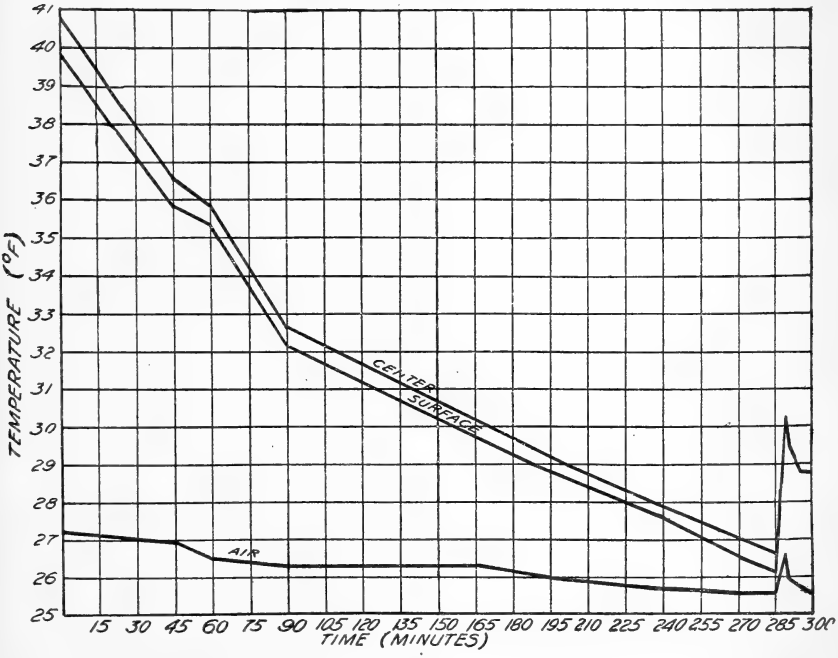


FIG. 1.—Temperatures at the center and near the surface of a Triumph potato as it undercooled to between 26° and 27° F. At this point it was inoculated by tapping it sharply with a pencil. As the potato froze, the temperature rose. When all the heat was liberated, the temperature of the potato reached 28.7° F. and remained several minutes. The temperature of the air bath to which the potato was exposed is also shown. Note the accompanying rise in the temperature of the surrounding air as the potato froze and liberated heat.

and 39.9° F. at the center. The difference in temperature at the surface and center gradually diminished until at 240 minutes there was a difference of only 0.4 of a degree. After this the difference became somewhat greater. In 285 minutes the temperature fell from 40.8° and 39.9° F. at the surface and center, respectively, to 26.7° and 26.2° F. At this point the potato was tapped sharply with a pencil, and freezing commenced. The temperature at both points began to rise as heat was liberated, due to crystallization of the water. In five minutes the temperature at the center rose to 30.2° F., and at the surface to 29.5° F. In 10 minutes the temperature at both points was practically the same, 28.7° F. This represents the freezing point.

The temperature of the air surrounding the potato at the time freezing took place rose from 25.6° to 26.6° F., due to heat liberated by the potato.

SUMMARY OF RESULTS OBTAINED BY DROPPING UNDERCOOLED POTATOES.

When undercooled at 28° F. and dropped 4 feet and 2 feet, the potatoes were severely bruised and showed extreme freezing injury of the vascular type. When dropped 1 foot, no bruising resulted, but all varieties froze except the Green Mountain and Spaulding No. 4. The type of injury was a faint blotch. When dropped 6, 4, and 2 inches once, no freezing injury resulted; but when dropped six times from these heights, severe injury followed. When bounced several times by dropping 1 inch, severe injury followed; in some cases the potatoes were frozen solid. When undercooled at 25° F., dropping once from 6, 4, and 2 inches caused injury.

Some further experiments were undertaken to determine what other forms of disturbances will inoculate undercooled potatoes. Duplicate lots of 12 specimens each of the Rural New Yorker variety were placed at 25° and 28° F. for 24 hours. At each temperature one lot was placed in the direct draft from an electric fan, while the other lot was protected from the draft to act as a check. At 25° F. 10 of the 12 potatoes in the draft showed injury; also 3 of the check lot were injured. At 28° F. no injury was found in either lot. A possible explanation for the fact that the potatoes froze when exposed at 25° F. to a strong current of air is that they undercooled much more rapidly than the lot not in the draft.

Two lots of six specimens each of Rural New Yorker were held at 28° F. for 24 hours, then wet and removed after another 24 hours. All of the lot that were wet were injured, while three of the lot that were not wet also were injured. In the next experiment two lots consisting of two of each variety were held at 28° F. for 24 hours; they were then wet and held for another 24 hours. The results obtained on examination are shown in Table VI.

TABLE VI.—*Freezing injury to potatoes of seven different varieties held at 28° F. for 24 hours and then wet while undercooled.*

Variety.	Wet.		Check.	
	Injured.	Uninjured.	Injured.	Uninjured.
Triumph	2	(a)	0	2
Irish Cobbler	2	0	0	2
Spaulding No. 4	0	2	0	2
American Giant	1	1	0	2
Rural New Yorker	2	0	1	1
Russet Rural	2	0	0	2
Green Mountain	1	1	0	2
Total	10	4	1	13

[a] Faint blotch.

The injury to these potatoes was not serious. All affected ones showed only a faint blotching. In the next experiment a mixed lot of 12 potatoes was held at 28° F. for 72 hours while supporting a 100-pound bag of sand. No evidence of injury was apparent.

An attempt was made to show that potatoes when undercooled are liable to be injured by ordinary handling. Duplicate half-bushel lots of potatoes representing four varieties, viz, Triumph, Russet Rural, Spaulding No. 4, and American Giant, were put together in four bags and held at 28° F. for 24 hours. Then one lot of two bags was rolled across the floor for a distance of about 30 feet. After 24 hours all were removed. Examination showed the results presented in Table VII.

TABLE VII.—*Freezing injury to potatoes of four different varieties held at 28° F. for 24 hours and then rolled 30 feet in a bag while undercooled.*

Variety.	Rolled.	Check.
	Per cent injured.	*Per cent injured.*
Triumph	10	0
Spaulding No. 4	0	0
American Giant	20	0
Russet Rural	50	0

A similar experiment was carried out in which two lots of 12 of each of the seven varieties were placed in two bags and held at 28° F. for 24 hours. One was then rolled about 50 feet. After another period of 24 hours all were removed and held for examination. The results obtained are shown in Table VIII.

TABLE VIII.—*Freezing injury to potatoes of seven different varieties held at 28° F. for 24 hours and then rolled 50 feet in a bag while undercooled.*

Variety.	Rolled.		Check.	
	Number injured.	Number uninjured.	Number injured.	Number uninjured.
Triumph	5	7	0	12
Irish Cobbler	12	0	0	12
Spaulding No. 4	0	12	0	12
American Giant	2	10	0	12
Rural New Yorker	12	0	0	12
Russet Rural	8	4	0	12
Green Mountain	7	5	0	12
Total	46	38	0	84

A distinct varietal difference is shown here. In neither experiment did the Spaulding No. 4 variety show injury. The American Giant was also less susceptible than the rest of the varieties. The Irish Cobbler, Rural New Yorker, and Russet Rural showed the greatest percentage of injury. In these experiments the potatoes did not receive the amount of jolting or rough handling that they might be

subjected to under commercial conditions. It is unfortunate that lack of material prevented further tests on a commercial basis. However, enough evidence was obtained to justify the publication of the results already obtained and to call the attention of growers and shippers of potatoes to the facts here presented.

SUMMARY.

(1) Potatoes freeze more quickly when exposed to a rapidly diminishing temperature than when the temperature diminishes slowly.

(2) Potatoes can be undercooled several degrees below their true freezing point and then warmed again above the freezing point without freezing injury, provided no ice formation takes place within the tissue.

(3) When undercooled, jarring resulting from rough handling or incidental to hauling is liable to cause potatoes to freeze.

(4) When undercooled in a temperature of 28° F., dropping from a height of 2 feet caused potatoes to bruise badly and to show extensive freezing injury. When dropped 1 foot they did not bruise, but showed frost injury. When dropped 6, 4, or 2 inches once no injury resulted, but when dropped six times frost injury followed. When wet, injury also resulted. Potatoes supporting a 100-pound weight were not injured.

(5) When undercooled at 28° F. and rolled across the floor for a distance of about 50 feet in bags freezing injury resulted.

(6) When undercooled at 25° F. and dropped 6, 4, and 2 inches once frost injury was apparent.

(7) After freezing commences it is progressive. The amount of injury caused within a stated time seems to depend upon the surrounding temperature.

(8) Immediately after inoculation the temperature of the potato rises to its true freezing point and remains for a varying length of time, depending upon the surrounding temperature.

(9) Some varieties apparently are inoculated more easily than others, even though their freezing point is higher.

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